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TIG-dressing of high strength steel butt welded connections – Part 1: weld toe geometry and local hardness

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Abstract

This paper presents the results of extensive measurements on weld toe geometry of as-welded and TIG-dressed butt welded connections in high strength steels S460, S690 and very high strength steels S890 and S1100. Descriptions of the measurement techniques and data analysis are presented. Four weld toe parameters have been formulated to characterize the weld toe: weld toe radius, weld toe angle, weld height and undercut. From the data can be concluded that TIG-dressing, on average, has a beneficial effect on the geometry of the weld toe. However, TIG-dressed weld toes have different appearances and as a result, weld toe parameters show more variation after TIG-dressing. An improvement of the weakest link is therefore not guaranteed. The reheating of weld material and surrounding parent material results in a new fusion zone (FZ) and heat affected zone (HAZ). Hardness measurements have been performed in all different zones and show an increase of hardness as a result of TIG-dressing, with an occasional exception in the very high strength steels.

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Keywords: TIG-dressing; butt weld; weld toe geometry; local hardness

1. Introduction

The use of very high strength steels, with yield strengths above 690 MPa, in civil engineering structures is relatively uncommon, although there are several interesting fields of application. Because of the relatively light weight of very high strength steel structures, especially bridges may benefit from the application of high strength

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steel. Most common standards have unfortunately only limited inclusion of very high strength steels, especially if fatigue strength is a limiting design criterion.

Several studies have demonstrated that unwelded plain material shows a linear relation between static strength and fatigue strength, but that the presence of notches results in a reduction of the fatigue strength (e.g. [1]). As a result, the fatigue strength of different steel grades is usually assumed to be equal in design codes. A possible solution is the use of weld improvement techniques such as TIG-dressing, to reduce the notch effect.

Nomenclature

θ	weld toe angle [degrees]
ρ	weld toe radius [mm]

2. TIG-dressing for fatigue life improvement

According to IIW recommendations, the aim of TIG-dressing is ‘to remove the weld toe flaws by re - melting the material at the weld toe. It also aims to reduce the local stress concentration effect of the local weld toe profile by providing a smooth transition between the plate and the weld face’ [2].

2.1. TIG-dressing process

The remelting of the weld toe is done with a standard TIG machine. The process is relatively sensitive to weld contaminants such as mill scale, rust, oil and paint. Therefore, the area to be TIG-dressed must be prepared by cleaning, wire brushing and light grinding. A lot of parameters influence the end result, such as the shielding gas, travel speed, welding current, position of the torch, etc. For exact specifications of the correct TIG - dressing procedure, reference is made to the IIW recommendations [2]. An example of a TIG-dressed specimen is shown in Fig. 1, the change in geometry regarding the weld toe is clear.

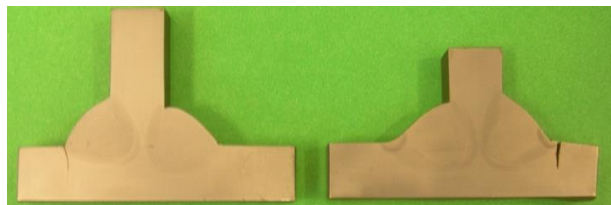


Fig. 1. Two fillet welded connections: as-welded connection on the left, TIG-dressed on the right

2.2. The influence of TIG-dressing on weld toe geometry and hardness according to literature

In the IIW recommendations on weld improvement techniques [2] detailed information is given on the TIG-dressing progress and some global information is given on the desired geometrical result. The torch position that theoretically results in the optimum shape and an actual specimen are depicted in Fig. 2.

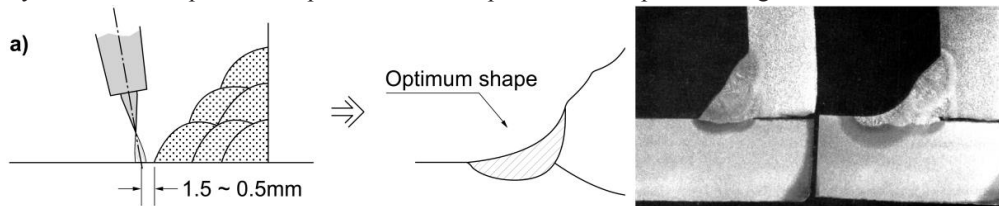


Fig. 2. Effect of TIG-dressing according to IIW recommendations (source: [1])

The geometrical changes of TIG-dressing can be quantified by defining the weld toe radius and weld toe angle (see Fig. 3). The main effect of TIG-dressing is the increase of the weld toe radius, which results in a lower stress concentration at the weld toe. The weld toe angle remains approximately the same for fillet welds, butt will be reduced for rather flat butt welds. The reduction of weld defects such as micro cracks and small inclusions is more difficult to quantify, and is covered in the scatter of the results of most researches. In fact, the TIG-dressing should reduce scatter by reducing the number of defects.

Various authors have done research on the change of weld toe radius as a result of TIG-dressing. Pedersen has collected a number of studies, of which the results are shown in Fig. 3 [3]. It is clear that a significant improvement in weld toe radius can be achieved by TIG-dressing, from an average radius of 1-1.5 mm to an average of 6 mm. However, the variation of the radius also increased compared with the as-welded condition. Unfortunately, it is not clear on which weld type these analyses are made, but the context suggests that the considered studies are mostly focused on fillet welds. The author has assumed a symmetrical distribution for the weld toe radii. Especially for the as-welded specimens this is unlikely, as this suggests the occurrence of many weld toe radii with negative values.

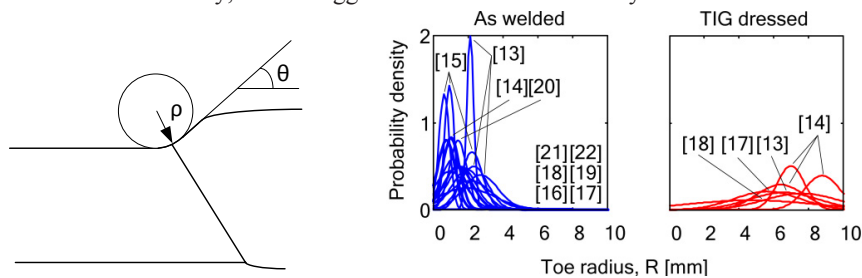


Fig. 3. Definition of weld toe radius and weld toe angle (left), comparison of weld toe radii in as-welded and TIG-dressed conditions; the numbers between brackets refer to the sources of the graphs in the original article (right) (source: [3])

Pedersen [4] has investigated the influence of TIG-dressing on the hardness of the weld and its surroundings. This investigation showed a hardness drop of 15% to 20% in the TIG-dressed area. Pedersen only considered Domex 700 steel ($f_y=700$ N/mm²).

3. Test setup

In this paper, the influence of the TIG-dressing process on the weld toe geometry and hardness of the weld region is analysed. For this, measurements have been performed on 9 plates with different specifications. All specimens contain a V-butt weld connecting two plates. In some cases these are both rolled steels (specimen marked with V), in some cases a rolled steel plate is connected to a cast steel plate (specimen marked with C). Steel grades S460, S690, S890 and S1100 have been investigated (specimens marked with 46, 69, 89 and 11). For example: plate C69 is a connection between a rolled and a cast plate of steel grade S690.

3.1. Measurements of weld toe geometry

To speed up the total process of measuring and preparation, silicon rubber casts are made of the welds, which are an exact negative reproduction of the weld. The casting process and the end product are depicted in Fig. 4. The casts of the welds are scanned with a laser sensor which is mounted to an X-Y motor. The X-Y motor has a precision of 1/160 mm in both directions and the laser has a resolution of 1/1000 mm. As a result of this, very precise measurements could be performed in a fine mesh. An overview of the setup is depicted in Fig. 4.

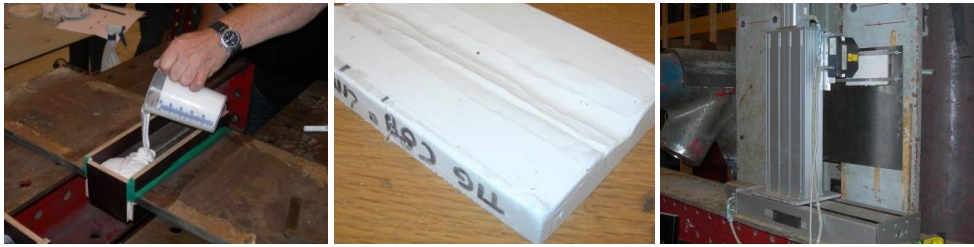


Fig. 4. Casting of the silicon rubber (left), silicon rubber cast of C89a plate (middle), overview of scanning device of casts (right)

3.2. Measurements of weld toe geometry

From all plates, a small piece of material has been polished and etched to distinguish the weld material, heat affected zone and parent material. Pijpers [5] has shown on similar specimens from the same material, that the hardness does not vary significantly over the thickness of the specimen, but only shows differences between the different weld influence zones (fusion zone 'FZ', heat affected zone 'HAZ' and base material 'BM'). Because the influence of TIG-dressing is only local, a comparison between the as-welded situation and TIG-dressed situation can therefore be made in one test piece. For the different measurement zones, see Fig. 5.

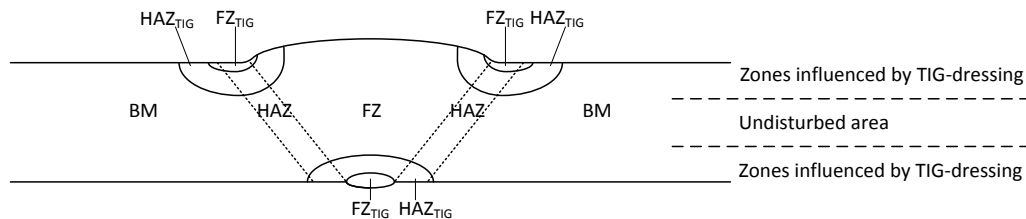


Fig. 5. Different measurement zones in a TIG-dressed specimen. Note that a large part of the original HAZ and FZ are not influenced by TIG-dressing and can thus be considered in the same condition as in the as-welded state

4. Analysis and results of weld toe geometry measurements

The output of the weld toe geometry measurements contains a full 3D image of the weld region (see Fig. 6). To investigate the change in weld toe geometry, cross sections of the weld at regular intervals have been analysed. On the specimens of which the geometry has been measured, fatigue tests have been carried out. Since all relevant specimens have shown failure from the weld cap, only the weld cap has been investigated [6].

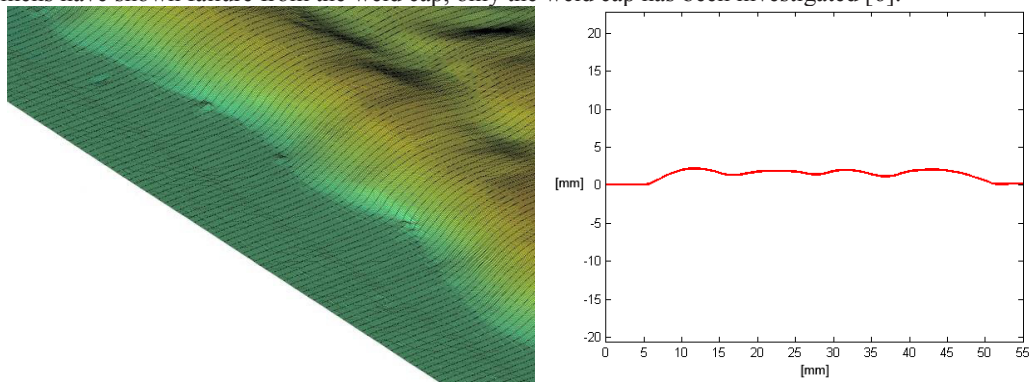


Fig. 6. 3D view in a $0.05 \times 0.5 \text{ mm}^2$ grid of a weld toe and adjacent base material in the as-welded conditions (left) and a cross section of the weld (right)

4.1. Post processing of raw results

Based on observations on the weld data, four parameters have been defined to describe the weld accurately. The four weld toe parameters, weld toe radius, weld toe angle, weld height and undercut, are depicted in Fig. 7. Simple numerical routines were used to determine the undercut, weld toe angle and weld height from the measured data. The determination of the weld toe radius is more complicated, since the forming of the weld toe is a natural random process and thus does not necessarily contain a clear, circular arch. To determine the weld toe radius, a fine grid is created around an estimated midpoint for the circle that coincides with the notch root. For each grid point, the distance to each data point in a user specified section of the weld geometry is calculated. The grid point that shows the least variation in these distances is the best suitable midpoint and the accompanying weld toe radius is determined by averaging all distances (see Fig. 7). The only subjective user input in this process is the starting point and endpoint of the notch analysis. To investigate the effect of this subjective user input, the same weld toe was analysed twice. Only minor differences between both analyses were visible [6]

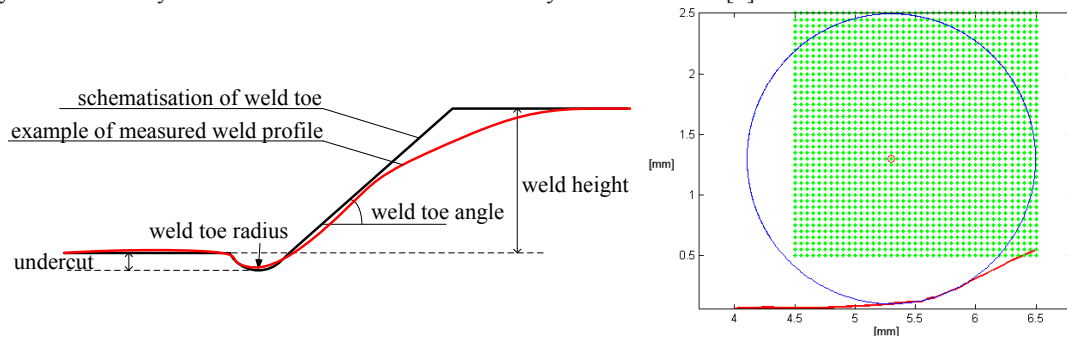


Fig. 7. Possible measured weld profile (exaggerated) and its accompanying schematisations with four weld toe parameters (left), numerical approximation of weld toe radius by drafting a fine grid of possible midpoints for the circle (right)

4.2. Observations on the changing weld toe

The analysis of weld geometries has resulted in around 750 radii, angles and undercuts and about 375 weld heights for both the as-welded condition and the TIG-dressed condition. The as-welded geometries all looked very similar, but the TIG-dressed geometries showed four characteristic shapes, which appeared in different quantities. The global shape of the observed weld toe shapes for both the as-welded and TIG-dressed condition are shown in Fig. 8.

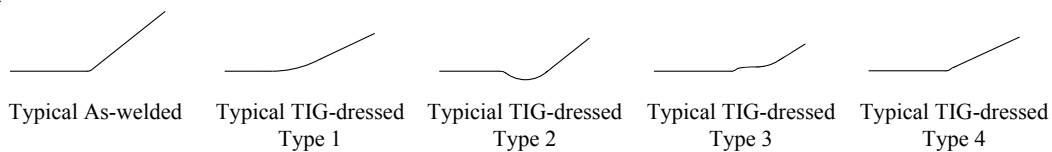


Fig. 8. Observed weld toe shapes (fictive geometries, for communication purposes only)

The observed geometries can be described as:

- Typical As-welded. The as-welded specimens generally have the same geometry. The parent material shows no great undercuts. The weld material starts after a relatively small radius. The angle of the weld material is rather steep.
- Typical TIG-dressed, Type 1. This is the desired effect of TIG-dressing (see Figure 2). The overall weld geometry is much smoother. The weld toe radius is much larger than in the as-welded state, and the weld toe angle is reduced.

- Typical TIG-dressed, Type 2. A significant undercut is visible, even to the naked eye. The undercut has depths up to about 0.5 mm. The weld toe radius is generally larger than observed in Type 1 and the weld toe angle somewhat steeper than for Type 1. Type 2 does occur, but not very frequently, and also not in every weld.
- Typical TIG-dressed, Type 3. To the eye this looks very similar to Type 1. However, a small ridge can be felt with a sharp object or the fingernail. In the measurements, the radius and angle of the first, and in all cases smallest, radius was measured. The weld angle of this type is similar to the weld angle of Type 1. Type 3 occurs rather frequently, and can be found in most, if not all studied welds.
- Typical TIG-dressed, Type 4. A small weld toe radius followed by a rather steep angle (similar to as-welded) for a very short distance. After this, the angle declines back to similar values as found in Type 1 and Type 3. Type 4 occurs far less frequent than Type 1 and Type 3.

It must be noted that all cross sections that are studied here are located in a limited number of welds, all performed by the same person with the same equipment.

4.3. Influence of steel grade and fabrications method of parent material

The studied welds are not necessarily comparable. As mentioned before, some of the specimens contain cast and rolled steel, and the specimens each are made from different steel grades. Furthermore, the cast steel plates were in most cases slightly thicker than the rolled steel plate to which it is connected. The S1100 specimens had a thickness of 20 mm instead of 25 mm. However, if the results of the various steel grades are compared, only slight differences are visible. For example, the variation of weld toe radii between the different steel grades is depicted in Table 1.

Table 1. Comparison of weld toe radii for different steel grades before and after TIG-dressing

Grade	As-welded		TIG-dressed	
	mean [mm]	stdev [mm]	mean [mm]	stdev [mm]
S1100	1.4188	1.0184	4.5360	2.9817
S890	1.5691	0.9458	4.9847	4.4375
S690	1.5210	1.1274	4.5058	3.1078
S460	1.8761	1.6850	3.6718	3.2851

The comparison between cast and rolled steel shows slightly larger differences, but not enough to be significant, considering the different sample sizes of cast and rolled steels. As mentioned earlier, some of the specimens are fabricated from rolled steel plates only, while others are a combination of rolled and cast steel plates. As a result, the weld toes adjacent to rolled parent material are three times greater in numbers. This can explain sharper peaks in weld toe parameter distributions concerning weld toes adjacent to cast parent material. An example of the comparison between cast and rolled steels is depicted in Figure 11. The figure shows similar distribution of weld toe radii, but indeed the cast steel shows a sharper peak.

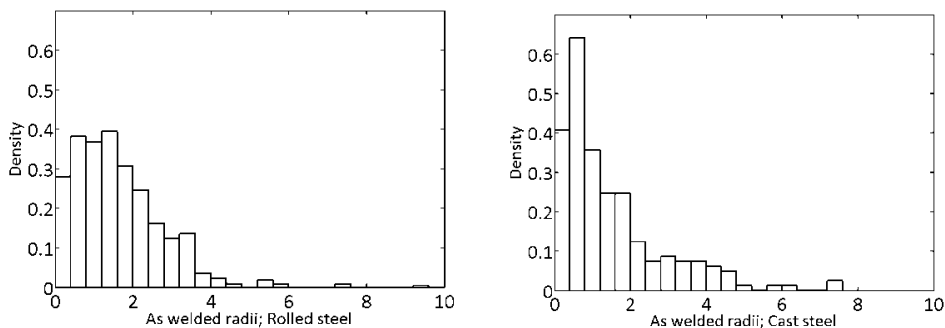


Fig. 9. Comparison of as-welded radii between weld toes containing rolled parent material and cast parent material

Based on the above results and further comparison of weld toe parameters between steel grades and weld toes containing cast or rolled parent material, it can be concluded that both the steel grade and fabrication method of the parent material have limited influence on the weld toe geometry [6].

4.4. Distribution of weld toe parameters before and after TIG-dressing

The following figures will show the distribution of the different weld toe parameters. All observed weld toe geometry types (see Fig. 8) are combined. Since the weld height (see Fig. 7) is not influenced by the TIG-dressing, for this weld toe parameter no comparison is made.

In Fig. 10 the weld toe radii before and after TIG-dressing are compared. It is clear that the average weld toe radius has increased significantly, but still a secondary peak of small radii remains present near the main peak of the as-welded radii. The spread of the data has increased after TIG-dressing, and the symmetrical distribution as assumed for other studies (see Fig. 3) clearly does not apply for this dataset. The increase in weld toe radius will have a positive effect on the stress concentrations at the weld toe. Since not all radii have shown improvement, it is unclear whether the weakest link has been improved.

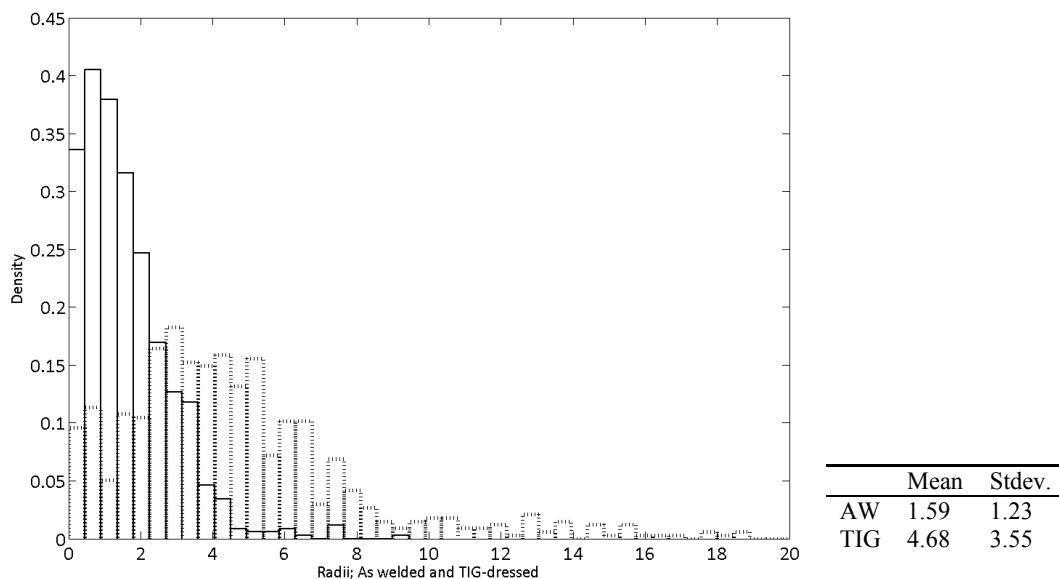


Fig. 10. Comparison of weld toe radii of as-welded (—) and TIG-dressed (---) specimens [mm]

In Fig. 11 the weld toe angles before and after TIG-dressing are compared. Apparently the weld toe angle is reduced due to the effect of TIG-dressing, which has a beneficial effect on the stress concentrations at the weld toe. The data shows a little decrease of the spread.

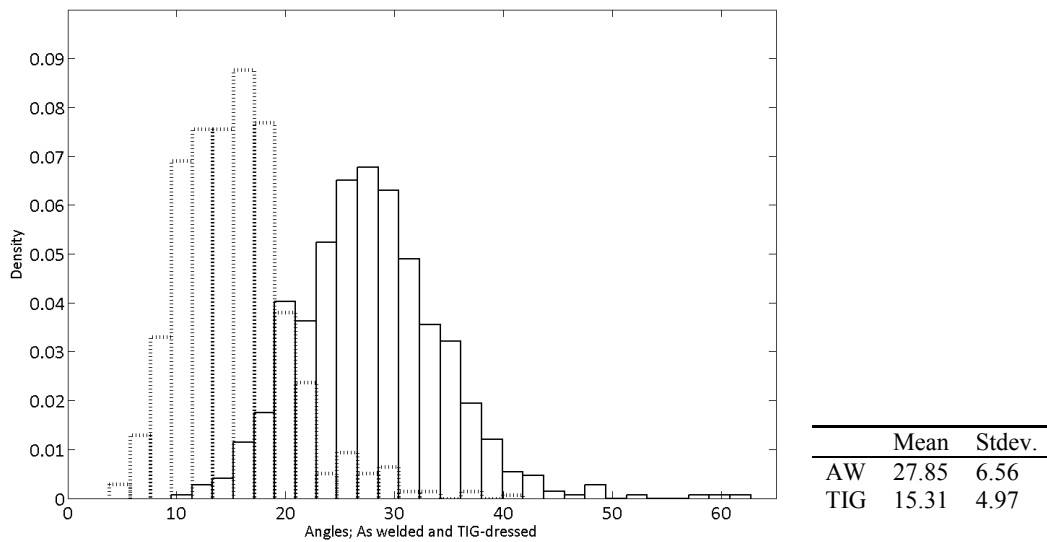


Fig. 11. Comparison of weld toe angles of as-welded (-) and TIG-dressed (- -) specimens [degrees]

In Fig. 12 the undercuts before and after TIG-dressing are compared. Most of the studied cross sections showed no or negligible undercuts. The number of non-zero undercuts has increased after TIG-dressing, but mostly the undercuts are still very small. The observed geometry including a large undercut (typical TIG-dressed, type 2, see Fig. 8) is relatively rare and is hardly visible in the distribution plot.

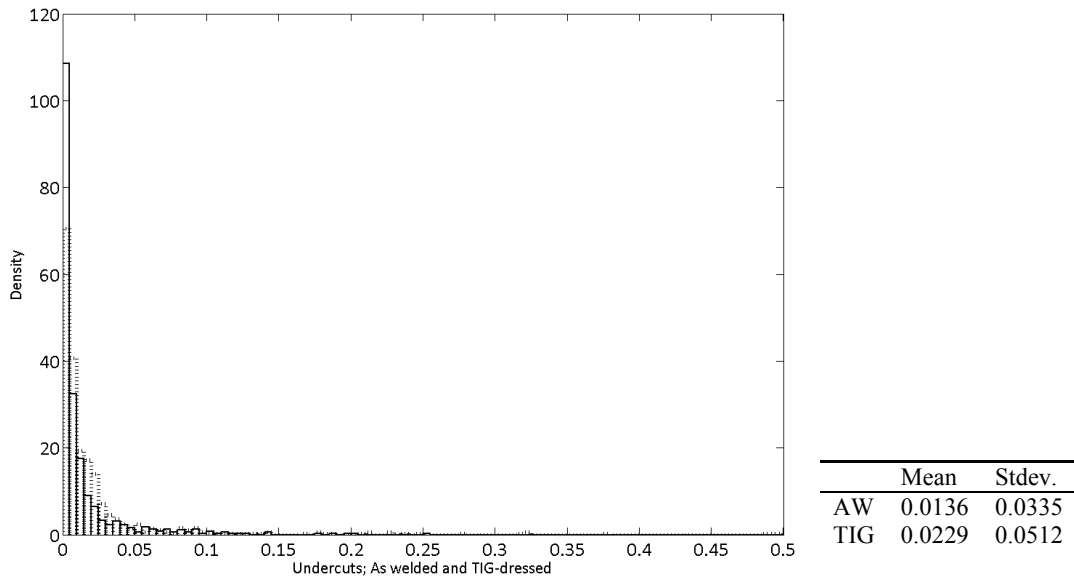


Fig. 12. Comparison of weld toe undercuts of as-welded (-) and TIG-dressed (- -) specimens [mm]

5. Results of hardness measurements

The results of the hardness measurements cannot be published here for all specimens. A few examples are shown, with conclusions based on all specimens. The full results can be obtained in [6].

In Fig. 13 the results of the hardness measurements are shown for the specimens with steel grade S1100. The diagrams show softening of the TIG-dressed area at the weld toe with respect to the surrounding, undisturbed areas in some cases. This is in accordance with the results from [4]. However, other areas show a hardness increase.

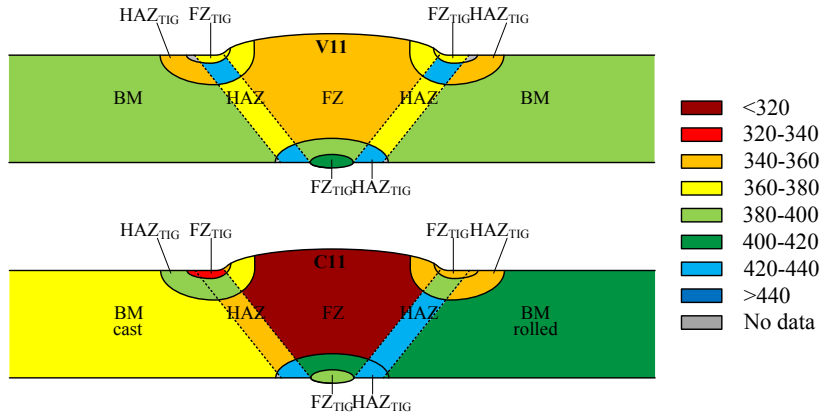


Fig. 13. Hardness measurement (HV10) for specimens with steel grade S1100. Note that the scale of the figure is different than in Fig. 14

In Fig. 14 the results of the hardness measurements are shown for the specimens with steel grade S460. In contrast with the very high strength specimens in Fig. 13, the TIG-dressed areas show a hardness increase, sometimes up to 50%. None of the zones that are influenced by TIG-dressing, both directly at the weld to or further into the base material or HAZ show any hardness decrease.

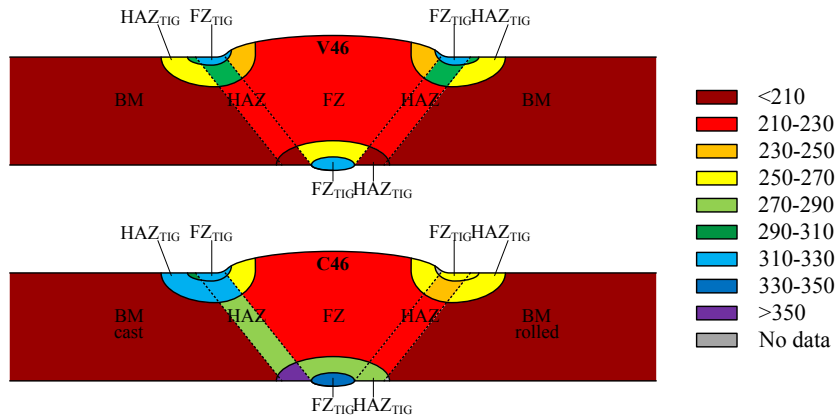


Fig. 14. Hardness measurements (HV10) for specimens with steel grade S460. Note that the scale of the figure is different from than in Fig. 13

The results shown by Fig. 13 and Fig. 14 reflect the general behaviour of all the specimens. In some cases in the very high grades (S1100 and S890) a hardness decrease is observed. In most other cases, the TIG-dressing increases hardness of the weld toe and its surroundings.

For unnotched material, a relation exists between static strength and fatigue strength. Since the hardness of steel can also be related to static strength, it is possible that TIG-dressing can also influence fatigue strength through hardness change of the notched area, mainly in the crack initiation life. In the considered specimens, primarily the lower strength (S460 and S690) specimens could benefit from such an effect.

6. Conclusions

6.1. Conclusions regarding the influence of TIG-dressing on the weld toe geometry

- As-welded weld toe geometries of the considered specimens generally shown one geometry variant. When these welds are TIG-dressed, different weld toe geometries can be observed (see Fig. 8). Different variants occur in different frequencies, but no single geometry variant dominates the measurements
- The peak value of the distributions of weld toe radii increases from ~1.0 mm for as-welded specimens to ~3.8 mm for TIG-dressed specimens. The TIG-dressed results also show a smaller peak in the region of the as-welded peak. The spread of the weld toe radii increases due to TIG-dressing.
- The peak value of the distribution of weld toe angles decreases from ~27.8° for as-welded specimens to ~15.3° for TIG-dressed specimens. The spread of the data before and after weld toe improvement is similar.
- The peak value of the distribution of undercuts is similar for the as-welded specimens as for the TIG-dressed specimens and lies at 0 mm. The number of non-zero undercuts is somewhat larger for the TIG-dressed specimens. One specific geometry variant shows significantly deeper undercuts than all other considered weld toe geometries, both as-welded as TIG-dressed. This geometry is also consistently associated with a very large weld toe radius and therefore will very likely not be the weakest link in fatigue.
- The discussed influences, with exception of the undercut influences, lead to an 'average' weld toe geometry with a lower stress concentration factor. However, due to the occurrence of a number of smaller weld toe radii in the TIG-dressed specimens, which is disproportionate with respect to the overall distribution, the theoretical improvement of the fatigue strength of a weakest link is not necessarily as high as is to be expected based on the improvement of the average weld toe geometry.

6.2. Conclusions regarding the influence of TIG-dressing on the hardness

- Most specimens showed hardness increase at the weld toe, where crack initiation is expected. In some cases a hardness drop was observed, but only in the very high strength steels
- If hardness can be linked to a fatigue life increase, the increases hardness of most specimens could have a positive influence on the fatigue life of the TIG-dressed weld toes.

7. Further research

The measured plates were later cut into 24 specimens on which tensile fatigue tests are carried out. The fatigue strength of these specimens has been modelled with notch stress theory on the basis of the geometry measurements in this publication. Results of the fatigue tests and modelling are available in [7].

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